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Double dipolar Halbach array for rheological measurements on magnetic fluids at variable magnetic flux density B

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Abstract. A new experimental setup for measuring rheological properties of magnetic fluids at variable magnetic flux density *B* with increased homogeneity is described. The proposed setup is mounted on a commercial strain-controlled ARES rotational rheometer. The magnetic flux is generated via two concentric Halbach cylindrical arrays made from permanent NdFeB magnets. The use of permanent magnets overcomes some of the disadvantages of electromagnets (e.g., excessive heating of the coils, formation of large radial stray fields, cost of electricity, cooling, etc). The performance of the new setup is tested for a magnetorheological fluid in both steady and oscillatory shear regimes.

1. Introduction

Magnetic fluids are stable suspensions of ferromagnetic particles in a carrier liquid, divided into two main classes: i) ferrofluids, containing nano-sized particles, and ii) magnetorheological (MR) fluids, with micron-sized particles [1].

The measurement of their rheological properties at different magnetic field strengths has been recently receiving increasing interest [2-6]. A commercial apparatus to perform such measurements is available from Anton Paar GmbH, the MRD-Magneto Rheological Device [5-8]. However, most of the work reported in the literature refers to custom-built devices, either adaptations to commercially available rheometers [3,4] or purpose-built devices [9-11].

Arrays of permanent magnets possessing a one-sided flux were first proposed in 1973 in a theoretical study by Mallinson [12]. Later, Klaus Halbach [13] constructed arrangements of permanent multipole magnets, which are nowadays known as Halbach arrays. These arrays can have a different number of magnetic dipoles, depending on the specific layout of the magnets. The optimized design and construction of dipolar Halbach circular arrays using permanent NdFeB magnets was described by Raich and Blümler [14]. These circular arrays confine the magnetic field mostly to the inner part of the cylinder, with a high homogeneity (typically $\Delta B/B$ < 1 %) being achieved.

In this work, a new experimental setup for measuring rheological properties of magnetic fluids at variable magnetic flux density B with increased homogeneity is described. The proposed setup is mounted on a commercial strain-controlled ARES rotational rheometer, and consists of two concentric Halbach cylindrical arrays made from permanent NdFeB magnets. The use of permanent magnets allows overcoming some of the disadvantages of using electromagnets as source for magnetic field (e.g., excessive heating of the coils, formation of large radial stray fields). The performance of the new setup was tested for a MR-fluid in both steady and oscillatory shear regimes.

2. Experimental

2.1. Description of the setup

Two distinct cylinders, each composed of two layers of dipolar Halbach circular arrays, were constructed. A homogeneous magnetic dipole inside each of the cylinders is obtained with this layout. The cylinders are placed inside one another, and can be rotated relatively to each other (Figure 1a). Hence, the resulting magnetic field at the center is the vector sum of the two individual fields and varies with the displacement angle θ.

The magnetic flux density was evaluated at the center of the setup, for different displacement angles θ. The B_y and B_z components of the magnetic flux were scanned in an area comprised of a circle with 28 mm diameter, in a grid with 2 mm spacing between each measurement point. The B_x component of the flux (along the axial direction of the setup) was found to be of the order of 0.1 mT for the maximum possible magnetic field on the setup (i.e., at $\theta = 0°$), and was therefore neglected for the other angles (see also [14]). The total planar magnetic flux density was determined by the vectorial sum of the two measured components, according to Equation 1:

$$\left|\vec{B}\right| = \sqrt{\left|\vec{B}_y\right|^2 + \left|\vec{B}_z\right|^2} \tag{1}$$

The magnetic flux density of this new setup covers a range of nearly zero to almost 0.6 T, with a homogeneity $\Delta B/B$ better than 1.8 % (Figure 1b). Non-uniformities in both the permanent magnets and in the dimensional tolerances of the parts hinder the attainment of the zero-field situation [14].

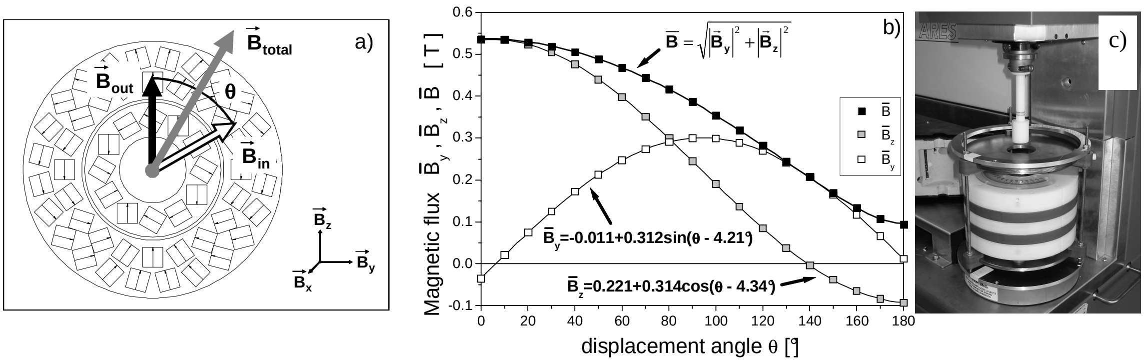

Figure 1. Basic characteristics of the new setup: a) schematics of the arrangement of double dipolar Halbach arrays; b) total magnetic flux density obtained, as a function of the displacement angle θ; c) the setup as mounted on the ARES rheometer.

With this Halbach layout, the magnetic stray field in the direction radial to the cylinders is greatly reduced. In the axial direction, the whole setup is magnetically shielded with metal sheets to avoid any interference coming from the magnetic stray field on the motor and torque transducer of the ARES. The measurement geometries consist of a cup combined with a concentric cylinder (Couette) or a 4-bladed vane. The geometries are made of polyoxymethylene to avoid disturbing the magnetic field during the measurements, as well as the formation of eddy currents (Figure 1c).

A commercial magnetorheological fluid grade MRF-132AD from LORD Corporation (Cary, North Carolina, USA) was used to assess the new setup. According to the manufacturer, the fluid contains 81.64 wt.-% of solids, suspended in a hydrocarbon-based carrier liquid. The mean size of the iron particles is around 6 µm.

2.2. Rheological experiments in steady shear

Stress growth curves at startup of steady shear were obtained for different constant shear rates and magnetic field strengths, until a steady shear regime was observed. For each shear rate, the viscosity was determined by averaging the steady shear zone. A consistent increase of the shear viscosity with increasing magnetic field was found (Figure 2a). This is better observed by plotting the relative viscosity, where an increase of the shear viscosity by a factor of about 30 to 175 was found for $B \neq 0$ (Figure 2b).

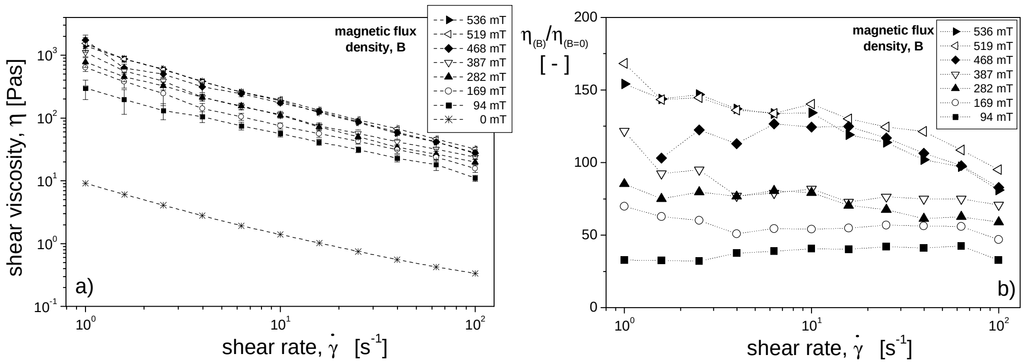

Figure 2. Steady shear viscosity as a function of shear rate, for different applied magnetic flux densities: a) absolute values; b) relative shear viscosity (for $B \neq 0$).

2.3. Rheological experiments in oscillatory shear

Strain sweep tests in oscillatory shear ($\omega_1/2\pi = 1$ Hz) were also performed. In the case of the shear storage modulus, G', an increase of the modulus in the linear regime ($\gamma_0 < 0.1$ %) by a factor of 175 was observed in the presence of the magnetic field. Also, a shift of the linear regime to higher strains was found to occur with increasing magnetic field (Figure 3a). In the presence of the magnetic field, a peak in G'' appears near the transition to the non-linear regime of deformations. This peak is also observed to shift to higher strain amplitudes with increasing magnetic flux density B (Figure 3b).

The rheological properties of the MR fluid used in this work were also measured independently in an external laboratory, using the commercially available Anton Paar MRD flow cell. In the presence of magnetic field, the results shown in the present work (both shear viscosity and dynamic moduli) are approximately one order of magnitude lower than the ones measured in the standard equipment. Nevertheless, both results are consistent and show exactly the same features, being only affected by a shift in the ordinate axis. Further work is on the way to evaluate whether a calibration procedure can be established, that could clarify the present results. Also, the implementation of a Hall sensor on the measuring geometry during the measurements can further help in clarifying this issue.

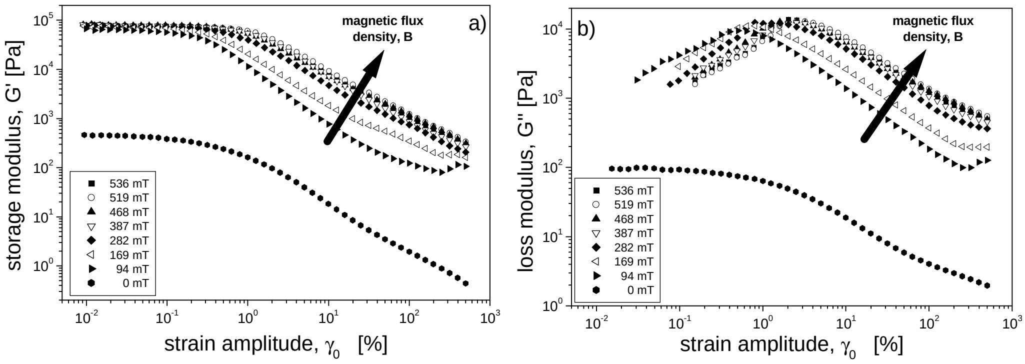

Figure 3. Dependence of the dynamic moduli on the shear strain amplitude, at different *B*.

3. Conclusions

The double dipolar Halbach array allows a varying magnetic field to be obtained, whilst maintaining a high field homogeneity. This setup is mounted on an ARES rheometer, and a commercial MR-fluid was used to evaluate its performance. A dependence on the magnetic field is observed for the dynamic moduli in oscillatory shear and also for the steady shear viscosity. These results are consistent with independent measurements performed in the standard accepted equipment.

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